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Research on the Layout of Real-Time Monitoring Sensors for Long-Span Cable-Stayed Bridges with Twin Towers

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Research on the Layout of Real-Time Monitoring Sensors for Long-Span Cable-Stayed Bridges with Twin Towers

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Abstract: Base on a long-span cable-stayed bridge with twin towers. According to the design data and the load test, FEM is established and modified to meet the actual structure. By using the theory of FEA and calculation of the design load and structural mechanics performance, “Theoretical spectra” of static characteristics of structures are established. On the basis of load test, the most unfavorable section and vulnerable parts of the bridge are obtained. Then “Standard spectrum” of bridge structure under the action of standard design load is established. Combining theoretical analysis with the sensor layout method commonly used in long-span cable-stayed bridges, the sensor layout scheme is finally obtained according to the "theoretical spectrum", the "standard spectrum" and the sensor optimization arrangement theory. The sensor placement method presented in this paper is feasible and effective, and provides a scientific theoretical basis for the sensor placement scheme. It can be used as a real-time monitoring sensor placement method for similar bridges.

1. Introduction

At present, the layout of real-time monitoring sensors for cable-stayed bridges is mostly based on past experience. Determine the number of monitoring projects and sensors based on project needs and investment budget. Round down the secondary monitoring content and select important typical section layout sensors. Of course, there are some monitoring systems that invest heavily and install a large number of sensors to get huge amounts of data. However, many of the data collected have no practical significance and pose certain difficulties for data transmission and processing. Therefore, how to use fewer sensors to be placed in important positions of structural monitoring and get the most valuable data is a problem that needs to be solved urgently.

This paper proposes the "three-spectrum analysis method" to conduct more scientific and rational monitoring of bridge structures and to judge the health of bridges, which includes "theoretical spectrum", "standard spectrum" and "random spectrum". The "spectrum" here is not a simple one or several curve, but refers to the load effects of the structure, including structural deformation, stress, strain, acceleration, etc. “Theoretical spectrum” refers to the theoretical calculation response of a structure under design loads. “Standard spectrum” refers to the measured response of the structure under the standard design load in the bridge load test. “Random spectrum” refers to the structural response of the daily operation process after the completion of the real bridge under random vehicle loads.

“Three-spectrum analysis” can not only be used to assess the health of the structure, but also has important guiding significance for the placement of the sensor. In order to improve the scientific, effective and economic performance of the sensor layout scheme, this paper takes the long-span double-tower cable-stayed bridge as the research object. Construct a "standard spectrum" of structural response and "theoretical spectrum" reflecting the mechanical performance of the structure. Combining with the theory of sensor optimization layout and the scientific and systematic comprehensive analysis, the sensor layout method is studied.

2. Engineering background

Fuzhou Huai'an Bridge is a large-span double-tower cable-stayed bridge with a main span of steel box girder and a side span of concrete box girder. The main bridge is 640m long and the bridge span is (45+67+416+67+45) m. It adopts a semi-floating system. The bridge layout is shown in Figure 1.

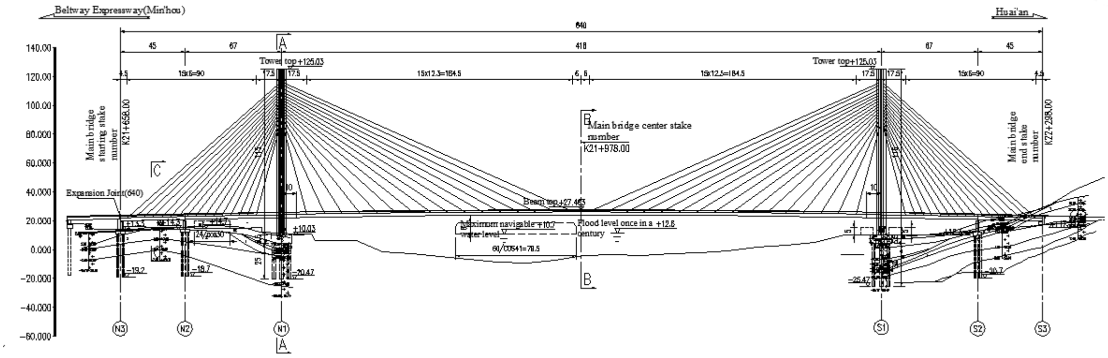

Fig.1 Bridge Layout

3. Load Effect Analysis Based on Modified FEM

The initial finite element model is modified by using the correction method based on dynamic parameters. From the calculation frequency and the measured frequency shown in Figure 2, it can be seen that the calculation frequency of the modified model is closer to the measured frequency, which is more in line with the real state of the real bridge. Based on the modified model, the load effect analysis is carried out to obtain the structural response under dead load, design load and overload condition, in order to arrange the sensor for the bridge.

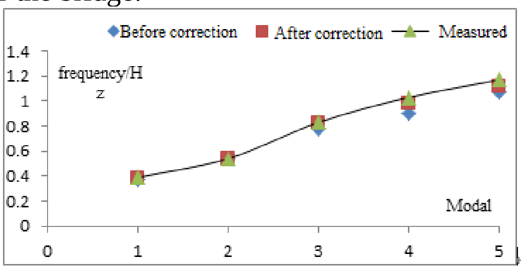

Fig.2 Calculated Frequency and Measured Frequency

4. Load test data analysis

The design load rating of the bridge is Highway Class I, and the load efficiency coefficient is guaranteed to be $\eta \geq 90\%$ .Vehicle layout based on the design internal force of the main control section of the bridge. The comparison between the measured values and calculated values of the deflection of the main girder and the longitudinal displacement of the main tower is shown in Table 1.The comparison between the measured value and the calculated value of the stress calculated by the main girder is shown in Table 2.

Tab.1 Comparison of Vertical Displacement of Main Girder and Longitudinal Displacement of Tower

Members	Section position	Measured value/*mm*	Calculate value/*mm*
Main girder	The deflection of mid-span(main span)	-216	-245

	The deflection of mid-span(side span)	-9	-14
Main tower	Longitudinal horizontal displacement of tower top	11	13

Note: The positive displacement of the pylon is 416m main span displacement.

Tab.2 Comparison of Stress Maxima of Main Beam Control Section

Section position	Measured value / *Mpa*	Calculate value / *Mpa*	Check coefficient
Mid-span section(main span)	41.2	49.1	0.84
Bearing Section(main tower)	1.2	2.0	0.6
Mid-span section(side span)	0.9	1.7	0.53

Through the analysis of the load test results:

- The maximum deflection of the side span is 9mm, the calculated value is 14mm, the maximum deflection of the main span is 216mm, the calculated value is 245mm, the longitudinal displacement of the tower is 11mm, and the calculated value is 13mm. The displacement extremes did not exceed the theoretical value. The above three sections can basically reflect the deformation condition of the whole bridge, so it should be used as an important measuring point for the later deformation monitoring.
- The measured values of the strains of each measuring point are smaller than the theoretical value, and the check coefficients are all less than 1. The tensile stress of the mid-span section of the main span is the largest, and the tensile stress of the mid-span section of the side span and bearing section is relatively large for the concrete main beam. Therefore, the above three sections should be regarded as important measurement points for the later strain monitoring.
- The long cable force near the mid-span section of the main span is relatively large and is more sensitive to the response of the load. Therefore, it should be used as an important measuring point for the later cable force monitoring.

5. Sensor placement

The sensor placement is mainly for monitoring items such as displacement, acceleration and strain [1].

5.1 Main girder acceleration sensor placement [2]

The main beam acceleration sensor placement adopts an effective independent method based on QR decomposition [3], combined with dynamic load test and finite element analysis. The placement of the sensor should satisfy the characteristics of comprehensive and representative measurement of the measuring point as much as possible, so as to more accurately identify the abnormal response and damage of the bridge[4].

- Acceleration point placement

Arrange the acceleration measurement points of the main beam by using the effective independent method based on QR decomposition, and the MAC modal guarantee criterion, dynamic load test and finite element result are used to check to ensure the rationality of the placement. The modal confidence matrix MAC is programmed by Matlab program [5].

The fifth-order vibration mode and frequency of the bridge are identified by environmental vibration test. Therefore, the vertical forward fifth-order mode is selected as the key monitoring object, and the sensor placement of the real-time monitoring system is studied.

The candidate measuring point is mainly located in the cable anchorage point. The mid-span anchor point spacing is 12m, the side-span anchor point spacing is 6m, and the total bridge has a total of 128 initial candidate points. Use the diag function in the Matlab program to extract the effective independent coefficients, and then perform candidate point screening according to the steps of the effective independent algorithm, the 14 and 16 measuring points can be arranged. The 14 measuring points are determined, and the adjustment of the measuring points in the scheme is partially adjusted. The final recommended layout scheme is shown in Figure 3.

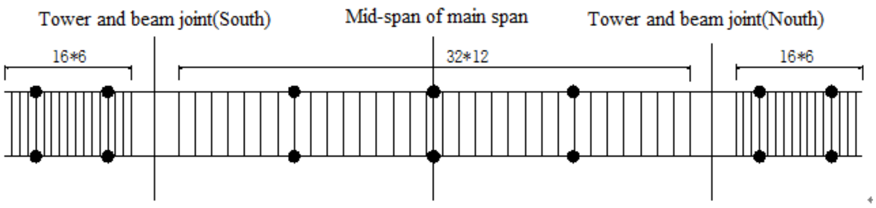

Fig.3 Recommended Layout of Acceleration Sensor

It can be verified from the FEA and the dynamic load test that the measurement points in this recommended scheme are basically at the position with the largest structural amplitude [6], and the distribution in the whole bridge is relatively uniform, which can ensure the comprehensiveness of the monitoring data.

5.2 Cable force acceleration sensor placement

The staying cable has an elastic support for the main beam and should also be focused on [7]. The cable stress near the main tower is small. The cable stress away from the main tower is large. In the range of the side span, the S11 and S16 cables have the greatest stress and the S14 stress increases most obviously. The M11 and M12 of the cable near the middle span have the greatest stress, and the M6 stress increase is the most obvious. Due to the high safety factor of the cable, it will not be damaged by the overload of the vehicle if the cable is not defective. However, the material of the stay cable is high-strength steel, which is prone to fatigue damage. After analysis, it is concluded that the side span cable S10~S16 and the main span cable M6~M10 are prone to fatigue damage.

In the past, the cable force sensor placement usually chose the longest cable or the cable with the largest cable force, and did not consider the fatigue problem of the cable. This article focuses on this aspect, the sensor is placed on the cable that is prone to fatigue damage and maximum force, that is, the side span S10~S16, the main span M6~M10, M16. The cable force sensor placement is shown in Figure 4.

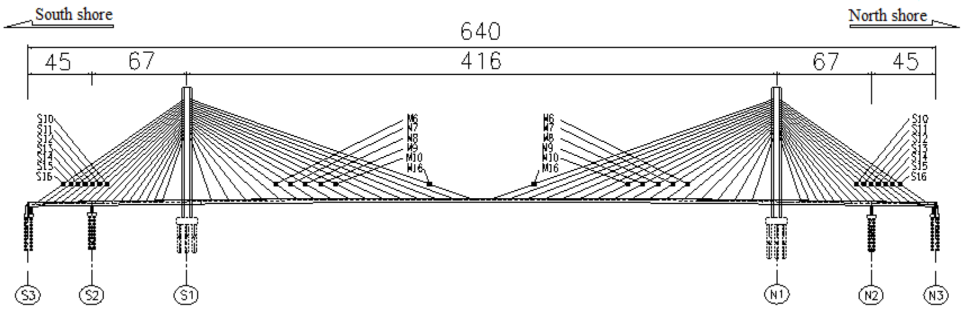

Fig.4 Layout of Cable Force Acceleration Sensor

5.3 Strain Sensor Placement

In this paper, based on the traditional strain sensor placement, the FEM and the stress control section obtained by the load test are considered to arrange the strain sensor. The stress of the main beam and the main tower is obtained through calculation and analysis. During the load increase process, the side span concrete box girder is mainly subjected to compressive stress. Although it is increasing, the overall value is small, and the stress at the steel-mixed joint and the nearby area is the largest. During the load increase process, the load on the main girder will be redistributed due to the elastic support of the stay cable. The phenomenon of alternating tensile and compressive stress occurs in the vicinity of the mid-span. Although the stress value is small, the steel is prone to fatigue in this case, and this area should also be focused.

The main tower is in a pressurized state as a whole, and the stress is increased from the top to the bottom in the anchorage section of the cable. After that, it increases linearly from top to bottom and reaches the peak at the junction of the tower and girder, which should be used as the key monitoring part of the real-time monitoring system.

Based on the above analysis, the layout of the main girder strain sensor is shown in Figure 5. The main tower layout scheme is to arrange one strain sensor on the north and south sides of the tower column at the junction of the tower and the beam. There are 8 sensors in the whole bridge.

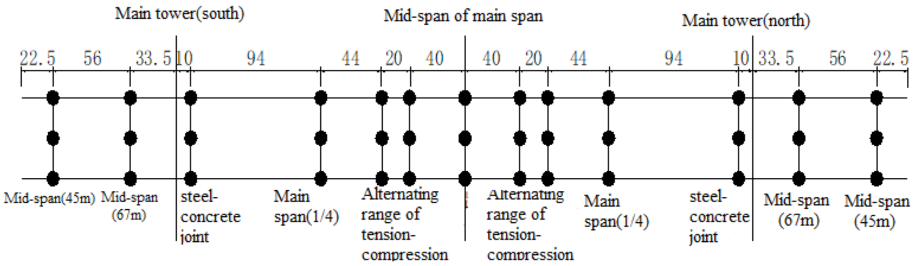

Fig.5 Layout of Strain Sensor for Main Girder

5.4 *Vertical displacement sensor placement*

The research object of this paper is the long-span double-tower cable-stayed bridge. Compared with arch bridges and continuous rigid frame systems, the cable-stayed bridge structural system has large structural deformation. The deformation of the bridge structure has a great influence on the driving comfort and the sense of safety. In addition, the deformation of the structure can also reflect the load distribution on the bridge and the variation of the internal force of the structure.

It can be seen from the figure that during the load increase process, the vertical deformation trend of the main beam is basically the same, and the deformation curve is continuous. The side span is relatively small displacement because the span is relatively small and the auxiliary pier. The mid-span vertical displacement is relatively large. Therefore, when considering the vertical displacement sensor arrangement, attention should be paid to the large area of the mid-span deformation and a small number of sensors should be arranged in the side span to obtain the full-bridge deformation curve.

Based on the above analysis, the layout scheme of the main beam deflection sensor is obtained. The side span sensor is arranged in the middle of the span. Since the main span deformation is large, the sensors are respectively arranged at the 8 points of the main span. A total of 11 deflection sensors are arranged on the whole bridge.

The final sensor placement scheme of full bridge is shown in Figure 6.

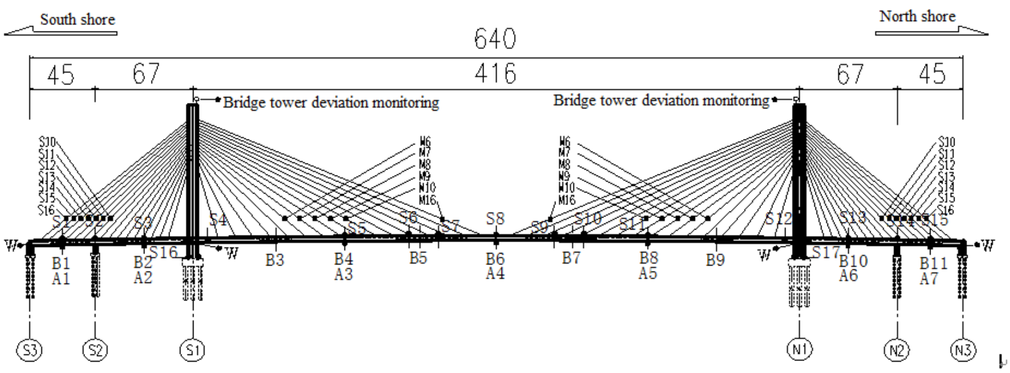

Fig.6 Layout Scheme of Full Bridge Sensor

6. Conclusion

- The initial FEM is more in line with the actual structural conditions, so as to construct the "theoretical spectrum" of the structural response, which has important theoretical guiding significance for the sensor placement.

- According to the load test data, the "standard spectrum" of the structural response under the standard design load is constructed, which plays an important role in the placement of the strain and vertical displacement sensors.
- Placement of vertical displacement sensor, strain sensor and cable force sensor based on "theoretical spectrum" and "standard spectrum" and acceleration sensor based on effective independent method are suitable, and the layout scheme of various sensors can be obtained.

In summary, the sensor placement method proposed in this paper is feasible and effective, and provides a scientific theoretical basis for the sensor layout scheme. It can be promoted as a layout method for real-time monitoring sensors of similar bridges.

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